Resonant Electron Transfer and Excitation in Two-, Three-, and Four-Electron $_{20}Ca^{q+}$ and $_{23}V^{q+}$ Ions Colliding with Helium

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Significant new evidence is reported for resonant transfer and excitation in ion-atom collisions. This process, which is analogous to dielectronic recombination, occurs when a target electron is captured simultaneously with the excitation of the projectile followed by photon emission. Strong resonant behavior with structure, in agreement with theoretical calculations, is observed in the cross section for projectile K x rays coincident with single electron capture for 100–360-MeV $_{20}Ca^{16+,17+,18+}$ and 180–460-MeV $_{23}V^{19+,20+,21+}$ ions colliding with helium.

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In the collision of an ion and an atom, fundamental atomic processes such as excitation, ionization, and charge transfer take place. Recent studies[1,2] indicate that excitation of the ion and capture of a bound target electron can occur simultaneously in a single collision to form an intermediate excited state. This state will subsequently decay by either photon emission or Auger electron emission. If the deexcitation is by photon emission, the entire process is termed resonant transfer and excitation (RTE). RTE is analogous to dielectronic recombination[3] (DR) which occurs when the capture of a free electron is accompanied by simultaneous excitation of the ion followed by photon emission.

In the case of DR, the formation of an intermediate state proceeds via an inverse Auger transition and hence is resonant for incident electron energies equal to the corresponding Auger electron energies. RTE is also a resonant process since the mechanism for the production of discrete intermediate states is analogous to an inverse Auger transition, except that the captured electron is initially (weakly) bound. The resonant condition for RTE occurs when the incident ion energy is such that the target electron energy in the rest frame of the ion is equal to one of the Auger electron energies. Many intermediate resonance states are possible for both RTE and DR, each one corresponding to an allowed Auger transition. A formal theoretical treatment of simultaneous charge transfer and excitation in ion-atom collisions has recently been developed by Feagin, Briggs, and Reeves.[4] Correlated two-electron processes such as RTE and DR are of fundamental interest; in addition these processes may have important applications in the investigation of astrophysical and laboratory plasmas.[5] Cross sections for both RTE[2] and DR[6] have been measured only recently.

As a specific example of the RTE mechanism consider a lithiumlike ion in its ground state ($1s^2 2s$) incident on a He target. In the collision, K-shell excitation of the ion occurs simultaneously with the capture of a bound target electron to produce an intermediate excited state such as ($1s2s2p^2$). Deexcitation of this intermediate state by K x-ray emission ($K\alpha$ in this case) completes the RTE process.

Experimentally, observation of a resonant behavior in the cross section for x rays (resulting from the decay of the intermediate excited state) coincident with electron capture identifies the RTE mechanisms and distinguishes it from competing processes. Since the velocity component of the target electrons (due to their orbital motion) along the beam axis contributes to the relative velocity, the widths of the individual resonance states reflect the distribution of target electron momenta, i.e., their Compton profile. Generally, this distribution is sufficiently wide to produce an overlapping of the separate intermediate resonance states such that individual states are not resolved. Instead, a broad resonantlike structure composed of the sum of contributions from many states is expected.[7]

The first experimental evidence for the existence of RTE was obtained in S^{13+} + Ar collisions.[2] However, the theoretical interpretation of these results is complicated by the complexity of the argon target with its three electronic shells. Investigation of RTE in collisions of ions with helium targets promises a simpler interpretation, since the target electrons are weakly bound compared to the kinetic energy of the projectile. Furthermore, a helium target is expected to give a smaller "resonant" width due to the narrower electron momentum distribution for the helium electrons compared to those in argon.

In this Letter significant new evidence for the RTE process is presented for calcium and vanadium ions with two, three, and four electrons incident on helium. Ions in all three incident charge states exhibit strong resonant behavior consisting of two maxima in the energy dependence of the cross section for projectile K x rays coincident with single electron capture. Calculations[8] of the RTE cross sections according to the method of Brandt[7] are in good overall agreement with the measurements.

Measurements were performed using the SuperHILAC at the Lawrence Berkeley Laboratory. The apparatus and the experimental procedures have been described elsewhere.[9] Total K x-ray yields and K x-ray yields coincident with single electron capture were measured as a function of gas pressure and found to be linear, indicating that single-collision conditions prevailed.

Figure 1(a) shows the cross section for total projectile K x-ray emission, $\sigma_{K\alpha\beta}$, and the cross section for projectile K x rays coincident with single capture, $\sigma_{K\alpha\beta}^{q-1}$, for ${}_{20}Ca^{16+,17+,18+}$ + He collisions. Relative uncertainties are generally less than $\pm 5\%$ for $\sigma_{K\alpha\beta}$ and less than $\pm 10\%$ for $\sigma_{K\alpha\beta}^{q-1}$. Systematic uncertainties due to x-ray detection efficiency and solid angle lead to an overall uncertainty in the absolute cross sections of about $\pm 20\%$. Figures 1(b) and 2(a) show the measured $\sigma_{K\alpha\beta}^{q-1}$ for ${}_{20}Ca^{17+}$ and ${}_{23}V^{20+}$ ions (lithiumlike in each case) and the calculated[8] RTE cross sections based on the method of Brandt.[7] Also shown are the calculated energy positions and relative contributions of the intermediate resonance states for dielectronic recombination.[10,11] For vanadium the measurements extend to 460 MeV which is the highest beam energy obtainable for ^{51}V at the SuperHILAC. It is seen from Fig. 1(a) for Ca^{q+} that $\sigma_{K\alpha\beta}$ varies slowly with energy while strong resonant behavior with two maxima is observed in the energy dependence of $\sigma_{K\alpha\beta}^{q-1}$. Similar results were obtained for vanadium ions with incident charge states $q = 19+$, $20+$, and $21+$. Contributions to the measured $\sigma_{K\alpha\beta}^{q-1}$ for heliumlike ${}_{20}Ca^{18+}$ and ${}_{23}V^{21+}$ from $1s2s$ metastable states due to capture (without accompanying excitation) to an excited state followed by x-ray emission are expected to be small.[12]

The data in Figs. 1 and 2(a), at the highest and lowest beam energies, indicate that the nonresonant contribution to $\sigma_{K\alpha\beta}^{q-1}$ is small, in contrast to the previous results[2] obtained for S^{13+} + Ar. This nonresonant part may be due to *uncorrelated* capture and excitation[7] in a single collision with one target atom. For helium targets the smaller nonresonant yield is probably due to the lower electron capture and K-shell excitation probabilities compared to Ar. Recent calculations[13] predict that, in the "resonance" region, the nonresonant part of $\sigma_{K\alpha\beta}^{q-1}$ should be a factor of about 10 lower than the resonant part for the collision systems studied here.[14]

The maxima in $\sigma_{K\alpha\beta}^{q-1}$ are attributed to RTE which occurs as a result of the formation of intermediate resonance states (for lithiumlike ions) such as $1s^2 2s \rightarrow 1s2s^2 2p$, $1s2s2p^2$, $1s2s^2 3p$, etc. followed by K x-ray emission. From Figs. 1(b) and 2(a) the shape, magnitude, and energy position of the calculated[8] RTE cross sections for Ca^{17+} and V^{20+} are observed to give reasonable overall agree-

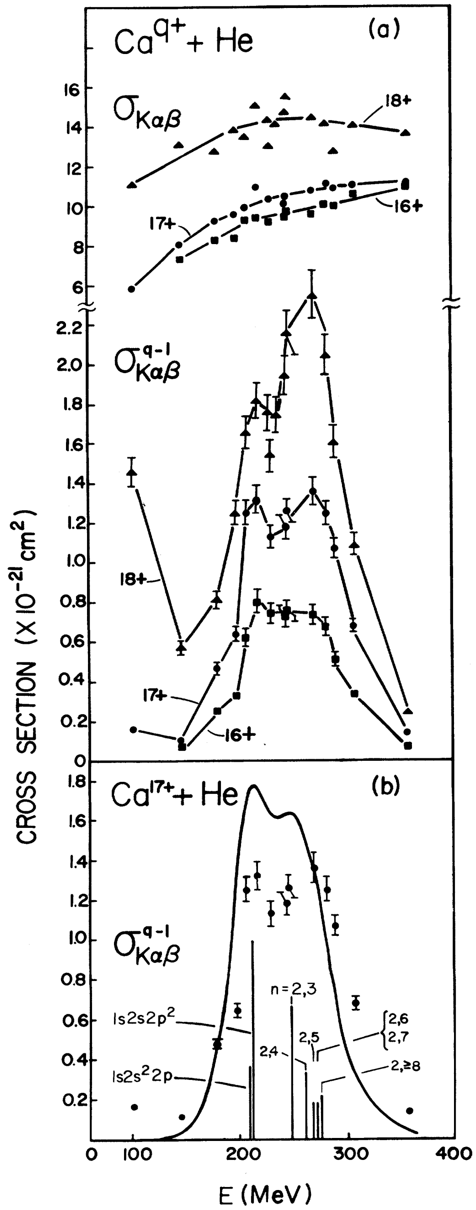

FIG. 1. (a) Projectile cross sections for 100–360 MeV $Ca^{q+}+He$ for $q=16+$, 17+, and 18+. $\sigma_{K\alpha\beta}$ is the cross section for the total calcium K x-ray production. $\sigma^{q-1}_{K\alpha\beta}$ is the cross section for calcium K x rays coincident with single-electron capture events. The solid lines are drawn to guide the eye. (b) $\sigma^{q-1}_{K\alpha\beta}$ for $Ca^{17+}+He$. The solid curve is the calculated (Ref. 8) RTE cross section. The vertical bars give the theoretical positions and relative intensities of the intermediate states for dielectronic recombination (Refs. 10 and 11). The notation $n=2, 3$, etc. refers to the principal quantum numbers of the two electrons in these intermediate states. The two states near 210 MeV are the $n=2, 2$ states.

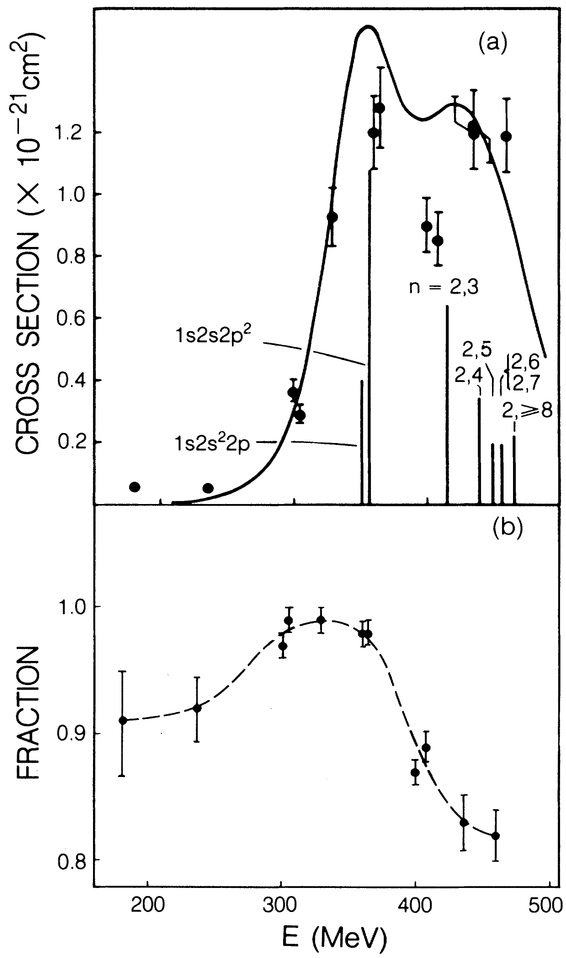

FIG. 2. (a) $\sigma^{q-1}_{K\alpha\beta}$ for $V^{20+}+He$. See caption for Fig. 1(b). (b) Ratio of $K\alpha$ coincidences with single electron capture to all K x-ray (i.e., $K\alpha+K\beta$) coincidences with single capture for V^{20+} ions. The line is drawn to guide the eye.

ment with the measured $\sigma^{q-1}_{K\alpha\beta}$.

Based on the theoretical dielectronic recombination energies[10,11] [see Figs. 1(b) and 2(a)] the lower-energy maximum corresponds to intermediate resonance states for which the excited and the captured electrons occupy levels with principal quantum numbers $n=2, 2$, i.e., $1s2s^2 2p$ and $1s2s2p^2$. The higher-energy maximum corresponds to intermediate states $1s2s^2 3p$, $1s2s2p3p$, $1s2s2p4p$, etc., for which $n=2, \geq 3$. Thus those intermediate states populated in the collision which give rise to the low-energy peak decay by $K\alpha$ transitions only, while the higher-energy peak contains contributions due to both $K\alpha$ and $K\beta$.

Figure 2(b) shows the ratio of $K\alpha$ coincidences with single electron capture to all K x-ray (i.e.,

$K\alpha + K\beta$) coincidences with single capture for V^{20+} ions. In the region of 360 MeV, this ratio is essentially unity. Thus, almost all the coincidences near 360 MeV are associated with $K\alpha$, indicating that the transitions which contribute to $\sigma_{K\alpha\beta}^{q-1}$ in this energy region are due to $n = 2, 2$ states. In the region of 435 MeV about 85% of the coincidences are with $K\alpha$. For energies $\lesssim 300$ MeV, the plotted ratio indicates the fraction of coincidences resulting from $K\alpha$ emission for uncorrelated capture and excitation events. Similar results are found for Ca^{17+} ions.

The correlation of certain energy regions within the resonant structure with specific n states, as predicted by the RTE calculations,[8] provides very strong evidence that the observed maxima in $\sigma_{K\alpha\beta}^{q-1}$ are, in fact, due to RTE. Furthermore, this partial resolution of the intermediate states into the groups $n = 2, 2$ and $n = 2, \geqslant 3$ is significant since it allows both the absolute magnitudes and the relative heights of these groups to be compared with theory.

The reasonable agreement of the positions of the maxima and the relative heights of the peaks in $\sigma_{K\alpha\beta}^{q-1}$ with the calculations [Figs. 1(b) and 2(a)] suggests that the relative probabilities for the population of groups of intermediate states with specific n values in the RTE process are nearly the same as those calculated for dielectronic recombination. Thus it would appear likely that RTE measurements will be useful in testing DR calculations, particularly for highly ionized ions.

In summary, important new evidence for the existence of resonant transfer and excitation has been presented. The use of a helium target simplifies the theoretical interpretation of the experimental results compared to previous measurements with many-electron targets. The observation of two maxima in the cross section for K x-ray production associated with electron capture provides a more detailed and critical test of the RTE theory and the calculated dielectronic recombination cross sections which go into the theory. The experimental results are in general agreement with the predictions of this theory. Apart from any connection to dielectronic recombination, the large resonant contribution to the coincidence yield due to RTE demonstrates the fundamental significance of this process and indicates the necessity of including RTE in theoretical formulations of ion-atom collision interactions.

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